REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Technical Paper	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Boeing		**8. PERFORMING ORGANIZATION REPORT**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20021018 043

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leilani Richardson
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	A		**19b. TELEPHONE NUMBER** *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

1 item enclosed

TP-FY99-Ø136

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MEMORANDUM FOR PRR (Contractor Publication)

8 June 1999

FROM: PROI (TI) (STINFO)

SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0136
Elvander, Wherley, and Claflin (Boeing), "Development of a Lightweight Thrust Chamber Assembly Utilizing in-situ Reinforced Silicon Nitride"

(Statement A)

AIAA Paper 99-2897

AIAA 99-2897

Development of a Lightweight Thrust Chamber Assembly Utilizing In-Situ Reinforced Silicon Nitride

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35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
20–24 June 1999
Los Angeles, California

DEVELOPMENT OF A LIGHTWEIGHT THRUST CHAMBER ASSEMBLY UTILIZING IN-SITU REINFORCED SILICON NITRIDE

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Abstract

The paper describes the status of the Light Weight Thrust Chamber Assembly (LWTCA) program currently underway at Boeing Rocketdyne Propulsion and Power, under contract with the US Air Force Research Laboratory. The goal of the program is to demonstrate technology which will lead to a 40% reduction in weight (including the nozzle), a 50% reduction in cost, a 75% reduction in part count and a 3% increase in specific impulse on a full scale, 400 klbf thrust LOX/hydrogen booster engine. The demonstration will be performed through the use of manufacturing technology demonstrator hardware and 60 klbf thrust hot-fire tests. The primary means to achieving these goals is by using in-situ reinforced silicon nitride for structural components. Silicon nitride is an advanced ceramic material that has high specific strength and fracture toughness, and can be cast to near-net part shape.

Tests to validate the material properties of in-situ reinforced silicon nitride are discussed, along with the resulting changes to traditional thrust chamber design as a result of the improved properties. The progress towards manufacturing and hot-fire testing a thrust chamber assembly from the material is also described.

1. Introduction

The Light Weight Thrust Chamber Assembly (LWTCA) program is an Air Force effort to develop and demonstrate technology that will lead to reductions in weight, cost, and part count, and to increased specific impulse (I_{sp}). Specific goals are a 40% reduction in weight (including the nozzle), a 50% reduction in cost, a 75% reduction in part count and a 3% increase in specific impulse in a full scale, 400 Klbf thrust LOx/LH_2 booster engine, relative to an SSME Block I baseline engine. These goals are part of the Air Force Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program, a broad effort to advance the state of the art in rocket propulsion.

The objective of the LWTCA program is to develop advanced lightweight materials and assembly processes to the point where they can be used in full-scale rocket engine components. Manufacturing technology demonstrator (MTD) hardware and 60 Klbf thrust hot-fire tests of subscale hardware will be used to demonstrate the attainment of program goals. MTDs are testbeds for fabrication and assembly processes. Their primary purpose is the validation of new manufacturing techniques, not hot-fire testing. When the processes are shown effective through the MTDs, hardware will be fabricated for hot-fire demonstration testing. The hardware to be fabricated and tested is the injector and main combustion chamber, from the propellant inlet manifolds to the nozzle attachment point.

The baseline material selected for development is in-situ reinforced silicon nitride, Si_3N_4, a monolithic ceramic with high specific strength and fracture toughness. Advanced brazing techniques using active braze alloys are being developed to join the ceramic and metal parts. The thrust chamber assembly is being designed to operate with a liquid oxygen (LOx)/hydrogen full flow staged combustion cycle. The thrust chamber design is based on that of the Universal Main Combustion Chamber, a design currently in use on other Rocketdyne development and production programs such as the X-33 linear aerospike thrusters and RS-68 engine.

2. Program Goals

The LWTCA program is part of the IHPRPT program, a joint research and development effort between the Department of Defense, NASA and industry to double the national rocket propulsion capability by the year 2010. Initiated in 1995 and administered by the Air Force Research Laboratory (AFRL) Propulsion

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Directorate located at Edwards AFB, IHPRPT encompasses across-the-board improvements in all relevant technology areas supporting boost, orbit transfer, spacecraft and tactical propulsion. By 2010, the IHPRPT technology advances should enable systems capable of delivering 50% more payload and costing 50% as much as current systems, resulting in a reduction in dollars-per-pound-to-low-earth-orbit of 60%. The advances will be achieved through a combination of technology initiatives, including investigations to increase the energy of propellants, the efficiency of combustion processes, and the combustion chamber operating pressures. Investigations will also be performed to decrease the inert weight of propulsion systems and life cycle costs, to improve the efficiency of thrust vector control systems, to decrease life cycle costs, and to improve reliability and environmental acceptability, safety, performance, and service life.[1]

The overall IHPRPT goals of 50% more payload to orbit at 50% of the cost translate into specific goals for cryogenic boost propulsion injectors and combustion chambers over the 15-year duration of the program, including a 3% increase in Isp, 50% reduction in costs, 40% reduction in weight, and 75% reduction in part count by the year 2005. These are the specific goals for the LWTCA program. The program focuses on the development of lightweight material technologies and low cost fabrication techniques applied to rocket engine injectors and combustion chambers.

3. In-Situ Reinforced Silicon Nitride

As previously stated, the baseline material chosen for development is in-situ reinforced silicon nitride (Si_3N_4). Sometimes referred to as in-situ toughened silicon nitride, this monolithic ceramic material exhibits high specific strength, fracture toughness, and maximum operating temperature (see Table. 1). AlliedSignal Ceramic Components (ASCC) of Torrance, CA, produces a type of in-situ reinforced Si_3N_4 known as AS800 which can be gel cast into nearly the final desired shape of the part with a minimum of after-cast processing. ASCC is teamed with Rocketdyne to develop AS800 components for the LWTCA program.

Table 1: Selected physical properties of AS800 Si_3N_4.

Maximum Use Temperature		2550°F
Flexural Strength (4-pt bend)	@ 70°F	104 ksi
	@ 2000°F	88 ksi
	@ 2300°F	83 ksi
	@ 2550°F	72 ksi
Fracture Toughness	@ 70°F	8.0 ksi•in$^{1/2}$
	@ 2200°F	5.9 ksi•in$^{1/2}$

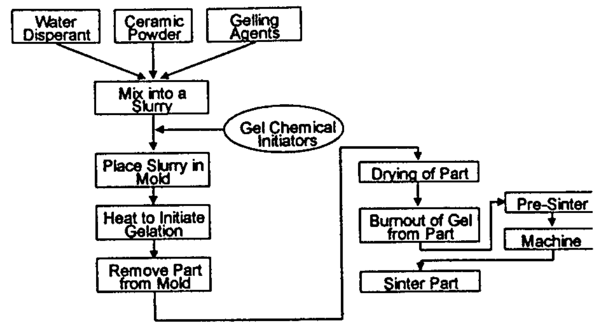

Figure 1: AS800 manufacturing process.

The AS800 gel casting process is analogous to metal investment casting, and is well suited to complex shapes and thin-walled surfaces. The gel casting process is shown schematically in Fig. 1. The ceramic powder is dispersed in water and gelling agents, and then poured into a mold, which is heated to moderate temperatures to induce gelation. The part is then removed from the mold and dried. At this point it is in its "green," or unsintered, state, and has enough strength to maintain its shape. If any additional machining it desired at this point, the part can be bisque fired, also referred to as pre-sintered, wherein it is placed in the sintering furnace under pressure and temperature long enough to develop sufficient strength to handle machining. The final stage of the process is the sintering (a.k.a. densification) of the part in the furnace at very high temperatures and pressures. If any final machining is subsequently necessary, diamond tooling is used to grind the part to its desired shape. The sintering process produces whisker-like grains, which produce the high specific strength and fracture toughness. In a sense, the monolithic ceramic is isotropically fiber-reinforced with its own ceramic material. The grains are visible in the scanning electron microscope (SEM) photograph shown in Fig. 2

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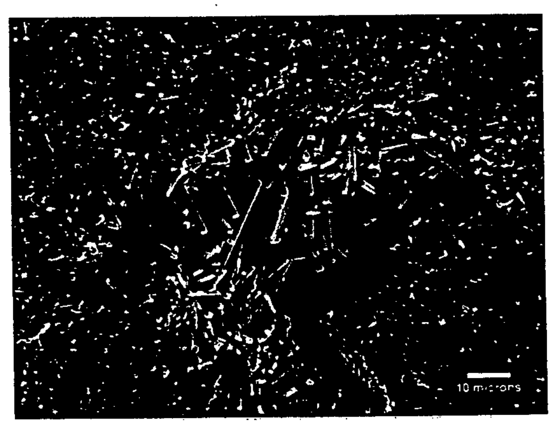


Figure 2: SEM view of AS800 grain structure.

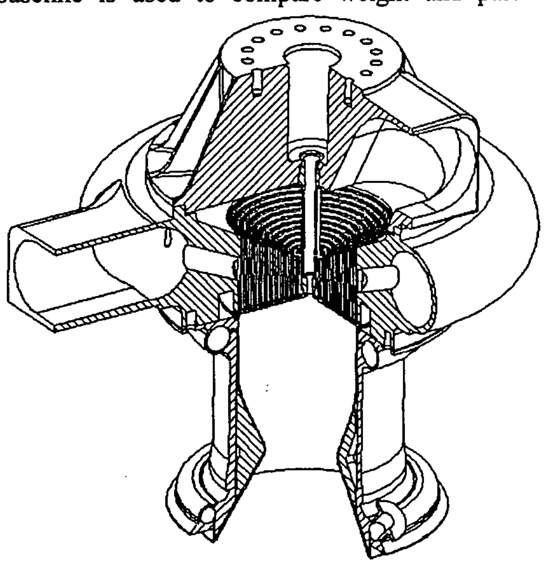
4. Program Description and Status

The LWTCA program is a 52-month effort lasting from June 1997 until September 2001. The program is divided into seven tasks, each of which will be subsequently discussed:

- Full scale thrust chamber system analyses (completed)
- Materials development (underway)
- Joining (underway)
- AS800 scale-up demonstration hardware (underway)
- Injector and thrust chamber MTDs (underway)
- Design and fabrication of lightweight, test-ready hardware (not yet begun)
- Testing (not yet begun)

4.a. Full Scale Thrust Chamber Assembly

The initial effort of the program involved the conceptual design of a 400 Klbf thrust engine that addressed the system level IHPRPT flow requirements using traditional metals in its design. This metal baseline is used to compare weight and part count



- 400 Klbf Vacuum Thrust
- Vacuum I_{sp} = 455 s
- FFSC LOx/LH_2 cycle
- P_c = 3010 psia
- Fuel Flow = 121 lbm/s
- Oxidizer Flow = 812 lbm/s
- Injector Max Dia = 42.0 in.
- Overall Length = 46.6 in.

Figure 3: 400 Klbf metal baseline design.

improvements as the program progresses. The engine design uses a LOx/LH_2 full flow staged combustion cycle (FFSC) based on the Integrated Powerhead Demonstrator (IPD), another element of the IHPRPT program focusing on performance improvements. The FFSC cycle combusts the LOx and LH_2 in separate preburners to power the turbopumps, such that the propellant inputs into the injector are gaseous oxygen and gaseous hydrogen mixed with small amounts of combusted product (steam). Whereas the IPD engine is designed to produce 250 Klbf thrust, the metal baseline designed for the LWTCA program was scaled up to 400 Klbf to better match the IHPRPT requirements. A cutaway drawing of the 400 Klbf metal baseline injector and chamber are shown in Fig. 3 along with performance data. Note the large inlet manifolds to accommodate the gaseous propellants.

The combustion chamber assembly process selected for the metal design is based on the Universal Main Combustion Chamber (UMCC), an internal Rocketdyne program which simplifies the assembly process and reduces the number of parts involved in the chamber (see Fig. 4). In the UMCC concept, two throat supports clamp together around a chamber liner that is slotted for regenerative cooling. The interior surfaces of the throat supports close out the middle portion of the coolant channels in the liner. The throat supports/liner assembly is then placed into the cylindrically shaped structural jacket, which closes out the top and bottom portions of the channels in the liner and is the primary load-bearing component of the assembly. The inlet and outlet manifolds are part of the structural jacket. The entire UMCC assembly is joined in one step using a hot isostatic press (HIP-) bond, wherein the liner is brazed to the throat supports and structural jacket in a pressurized furnace while drawing a vacuum on the coolant channels. The UMCC approach to chamber assembly is currently utilized in both the RS-68 engine and thrusters for the X-33 linear aerospike engine.

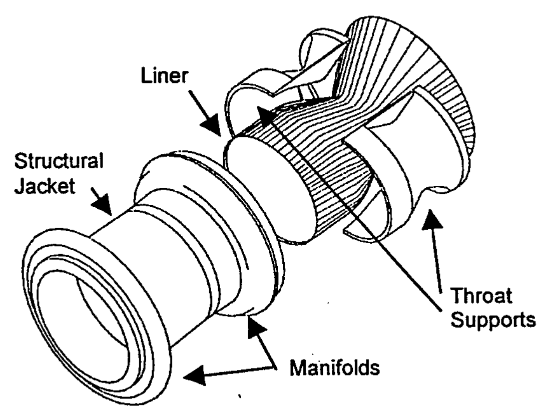


Figure 4: UMCC fabrication process.

For the metal baseline design, NARloy-Z, a high strength copper alloy, is selected as the material for the chamber liner. The throat supports and structural jacket are modeled using JBK-75, a castable ferrous alloy.

The injector is shown in an expanded view in Fig. 5. The injector consists of a main body which houses the fuel manifold, the GOx dome, the injector elements and the faceplate. The metal baseline configuration uses Haynes 188, a nickel-based alloy, for the injector body, GOx dome and injector posts. Porous stainless steel (commonly known by its trade name, Rigimesh) is baselined for the faceplate.

It is important to note that the full scale metal baseline is a design that will never actually be fabricated. As the materials and process technology develops, the full-scale design will be updated to demonstrate that the IHPRPT goals are met when applied to the full-scale engine. This design will also be used to feed full scale system level changes into the subscale (60 Klbf thrust) hardware design. The design establishes the flow conditions which the advanced materials and assembly processes will be designed to operate in, and which will be applied to the subscale thrust chamber assembly design and test matrix to ensure applicability and scalability of the subscale test results to the final full scale design.

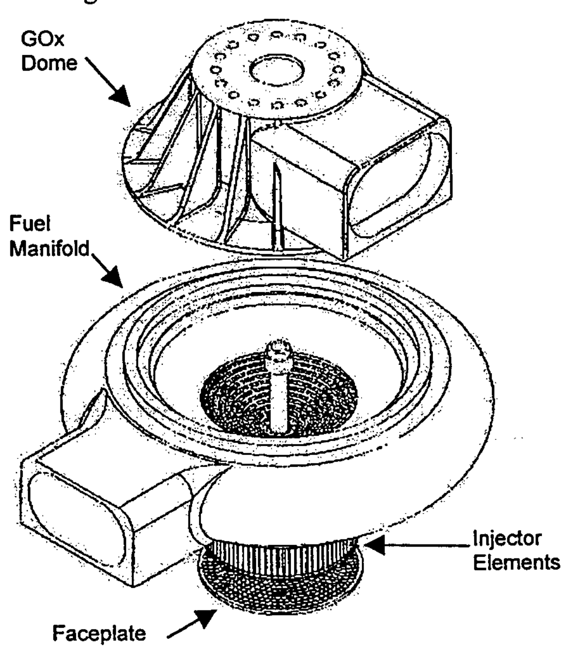


Figure 5: Injector for metal baseline.

4.b. Materials Development

The second phase of the LWTCA program involves the selection of the baseline material and comparing to other materials and processes. Materials were evaluated based on their applicability to specific components of the thrust chamber assembly. Table 2 shows the different materials considered for the different components.

The materials were considered based on a combination of qualitative and quantitative factors, including but not limited to specific strength, bulk material cost, coefficient of thermal expansion, ductility, modulus of elasticity, thermal conductivity, porosity, ease of fabrication and material maturity. AS800 gel cast silicon nitride was selected as the baseline material for the throat supports, structural jacket, injector body and GOx dome. NARloy-Z and Rigimesh were determined to still be the best materials for the chamber liner and faceplate, respectively.

Although AS800 is used in a variety of applications, a rocket engine thrust chamber assembly subjects the material to somewhat unique operating conditions as a result of cryogenic fuel moving through the assembly to cool the chamber liner. In order to better understand Si_3N_4, tests were conducted to characterize its physical properties at ambient, cryogenic and elevated temperature conditions. ASCC provided samples machined into the necessary geometries for the various characterization tests. The characterization tests are used to enhance the understanding of the material and develop a database providing the basis for an effective design. The test matrix is shown below in Table 3. To date, 217 samples have been evaluated and AS800 properties have met or exceeded expectations.

Table 2: Advanced materials evaluated.

Material Considered / Applicable Component(s)	Structural Jacket/ Throat Supports	Injector	Faceplate	Chamber Liner
Fiberite Polymer Matrix Composite (IM-7/977-2)	X			
Starmet BeAl	X	X		
Brush Wellman BeAl	X	X		
Metal Matrix Composite	X	X		
Hoechst Liquid Crystal Polymer Vectra B230	X			
Hoechst Liquid Crystal Polymer Vectra A230	X			
AlliedSignal Composites Primex Al_2O_3/Al	X			
AlliedSignal Composites C/SiC Plain Weave		X		
AlliedSignal Composites C/E-SiC Plain Weave		X		
AlliedSignal Composites SiC/E-SiC Plain Weave		X		
AlliedSignal Composites Dimox 8HS		X		
Coors Cu/Alumina	X			
NARloy-Z				X
Hypertherm C/SiC			X	X
Oxide Dispersion Strengthened Copper				X
Powdered Cu-Cr-Nb				X
Rigimesh			X	
AS800	X	X		

Table 3: AS800 characterization matrix.

Test	Test Description	Number of Specimens Tested: Cryo -300°F	Amb	Elev. 1000°F
Tensile	Fast Fracture	15		
	Fast Fracture	12	12	12
4-Point Bend	Fast Fracture	12	8	12
	Fast Fracture		12	
Compression	Fast Fracture	2	4	2
Environmental Exposure	H_2 @ -350°F and 6,400 psi for 30 Minutes		6	
	H_2 @ -350°F and 6,400 psi for 24 Hours		6	
	H_2O @ 800°F and 1,035 psi for 30 Minutes		6	
	H_2O @ 800°F and 1,035 psi for 30 Minutes		6	
	H_2O @ 800°F and 1,453 psi for 24 Hours		6	
	H_2O @ 800°F and 1,453 psi for 24 Hours		6	
	H_2 with10wt% H_2O @ 800°F and 3,690psi for 30 Min		6	
	H_2 with10wt% H_2O @ 800°F and 3,525psi for 25 Hrs,		6	
	H_2 with10wt% H_2O @ 800°F and 3,600psi for 30 Min		5	
	H_2 with10wt% H_2O @ 800°F and 3,600psi for 25 Hrs		6	
	He with 10wt% H_2O @ 800°F and 3,600 psi for 30 Min		6	
	He with 10wt% H_2O @ 800°F and 3,600 psi for 30 Min		6	
	He with 10wt% H_2O @ 800°F and 3,600 psi for 24 Hrs		6	
	He with 10wt% H_2O @ 800°F and 3,600 psi for 24 Hrs		6	
	O_2 with10wt% H_2O @ 800°F and 3,600psi for 30 Min		6	
	O_2 with10wt% H_2O @ 800°F and 3,600psi for 30 Min		6	
	O_2 with10wt% H_2O @ 800°F and 3,600psi for 24 Hrs		6	
	O_2 with10wt% H_2O @ 800°F and 3,600psi for 24 Hrs		6	
Interrupted Stress Rupture	110% Design Stress, 125% Design Life	6	6	6
Thermal Cycle	50 Cycles from 1800°F to LN_2 Quench plus		6	
	50 Cycles from 2200°F to LN_2 Quench			
	100 Cycles from 2200°F to LN_2 Quench		4	
Fracture Toughness	Vickers indent (20Kg) followed by std 4 pt bend, indent	4	4	6
	surface placed in tension at the indicated test temp			
	Conventional fracture toughness test	4		4
Low Cycle Fatigue	300 cycles @ Max. Stress & Combined Thermal Cycle	3	1	2
Elastic Modulus/Poisson's	Unknown. Test & data provided by the U of Dayton		6	

4.c. Joining

One of the design issues involved with utilizing Si_3N_4 in a thrust chamber assembly is the mismatch of the coefficients of thermal expansion (CTE) between the ceramic and metal components. Of particular concern is the joint between the NARloy-Z chamber liner and Si_3N_4 throat supports and structural jacket, since the CTE of the copper alloy is several times that of the ceramic. The UMCC approach to this joint, when the chamber assembly is entirely metallic, is to cover the copper liner with braze foil and attach it to the throat supports and structural jacket during the HIP-bond process. Ceramic materials preclude HIP-bonding, however, and the CTE mismatch in the joint generates such significant stresses that conventional brazing techniques are also inadequate, prompting the development of more sophisticated techniques to overcome this problem.

Under an internally funded development program, over one hundred samples of AS800 were supplied by ASCC to test advanced brazing approaches (Fig. 6). Copper alloy was attached to the samples with various braze alloys and the joints were tested for peel, tensile and shear strengths. A copper-silver active braze alloy was eventually selected.

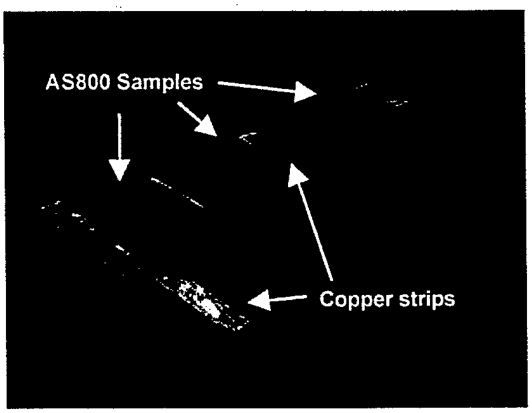


Figure 6: AS800 Si_3N_4 samples for brazing development.

Rocketdyne is working with Refrac Systems of Phoenix, AZ to optimize the brazing technique. Several flat samples of AS800 with manifolds have been brazed to a copper plate with channels milled into it, simulating the chamber liner (Fig. 7). Stainless steel tubes are brazed to the manifolds and the flat plate specimens are burst test with water to determine the joint integrity. The samples tested to date have exceeded expectations.

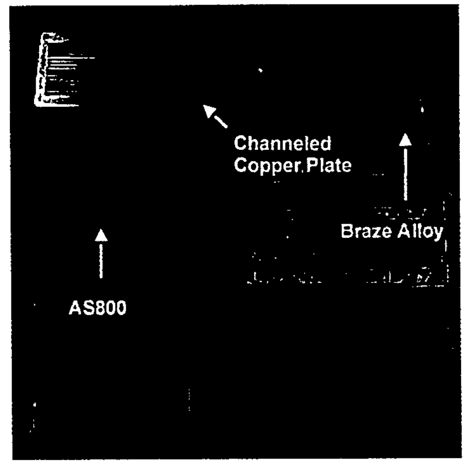


Figure 7: Burst plate sample.

4.d. AS800 Scale-Up Demonstration Hardware

To support the scaling up of AS800 to the sizes necessary for this program, ASCC is fabricating demonstration hardware. This hardware is not of the maturity required for an MTD; rather it is being developed to determine what, if any, fabrication issues exist which need to be overcome before committing to MTD fabrication. A cylinder approximately 12 in. long and 6 in. diameter was fabricated to demonstrate the scale-up of manufacturing process (Fig. 8). A slotted NARloy-Z cylinder will be bonded into the AS800 to mitigate the bonding risks prior to assembly of the MTDs. A subscale throat support design has been generated by Rocketdyne and delivered to ASCC for fabrication. This design contains an internal cavity that will not exist on future hardware, but will demonstrate the ability to cast manifold cavities with AS800. Fabrication of this initial throat support hardware will evidence any deficiencies in the fabrication process prior to committing to MTD hardware. A drawing of the throat is shown in Fig. 9.

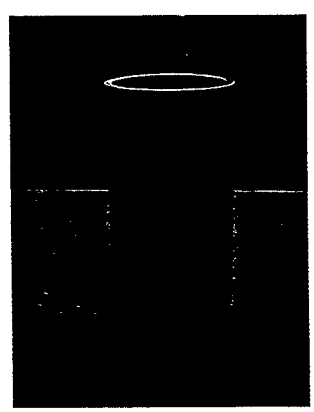


Figure 8: AS800 demonstration cylinder.

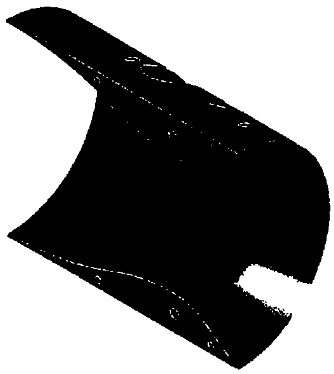


Figure 9: AS800 demonstration throat support.

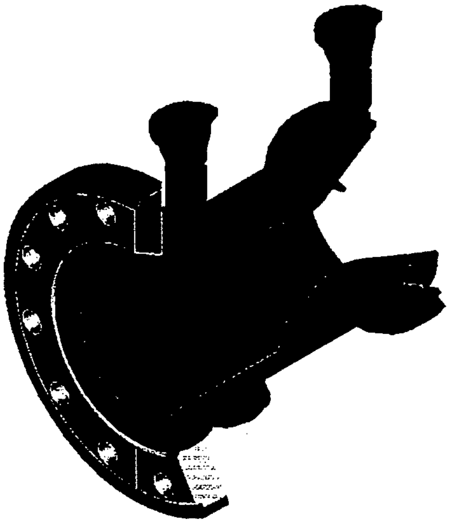


Figure 10: Chamber MTD design.

4.e. Injector and Thrust Chamber Manufacturing Technology Demonstrators

Prior to committing to fabrication of the lightweight test hardware, MTDs will be fabricated to verify material and process maturity. Two injector and two combustion chamber MTDs will be fabricated.

Both the injector and chamber MTDs will be designed as if they were going to be hot-fire tested. The injector element type will be selected based on faceplate heat flux, combustion stability, combustion efficiency and packaging. The baseline element is a 10° conical impinging element similar to that used on the IPD injector. The size and location of the injector will be selected to minimize injection stability response while achieving 99% combustion efficiency. The element geometry will be optimized to minimize faceplate and chamber heat flux within the stability and performance constraints. The injector will be fabricated using AS800 for the injector body, GOx dome, and LOx posts, then brazing them into an assembly along with the faceplate and injector tips, which are currently baselined as metallic materials to enable sufficient cooling.

The combustion chamber MTD will be designed to take advantage of the cost and part count advantages of the UMCC fabrication technique described above. The assembly will be comprised of a NARloy-Z liner, two Si_3N_4 throat support halves and a Si_3N_4 structural jacket. Design of the chamber will depend on the injector design. The chamber contraction ratio of 3.0 has been selected as the minimum required for optimum injector element packaging. The injector-to-chamber throat length, L', has been minimized (to minimize weight and cost) by employing injector elements which promote rapid mixing. The chamber convergent section geometry has been optimized for minimum total heat load, minimum peak heat flux and maximum acoustic energy dissipation (combustion stability). A drawing of the MTD appears as Fig. 10.

After fabrication of the MTDs, each will undergo x-ray, dye penetrant and dimensional inspection to verify the form, fit and function of the MTDs. Because material flaws are acceptable in the MTDs, the units will not be proof pressure tested.

4.f. Design and Fabrication of Lightweight, Test-Ready Hardware

To support 60 Klbf thrust hot-fire verification testing, two test-ready lightweight injectors and two lightweight combustion chambers will be fabricated. The design of the injectors and chambers will be revised as necessary, incorporating lessons learned from the MTDs. The hardware will undergo x-ray, dye penetrant, dimensional and proof pressure testing. One chamber and one injector will each be delivered to the test stand, and one each held as a backup.

4.g. Testing

Hot-fire testing of the hardware will be conducted at the Rocketdyne Santa Susana Field Laboratory near Canoga Park, California. Existing preburners will be used to provide an accurate full-scale thermochemical environment to the lightweight injector during testing. Figure 11 shows a drawing of the test assembly. After preliminary testing to check out the test stand hardware, mainstage testing will progress from a chamber pressure of 2000 psia to 3010 psia, the design pressure of the full-scale 400 Klbf thrust design.

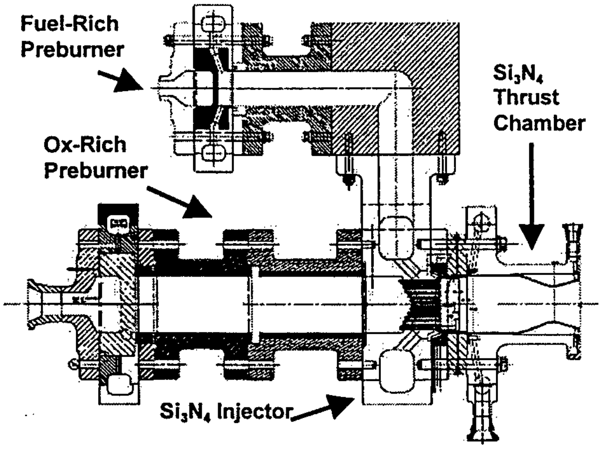


Figure 11: LWTCA test assembly.

5. Summary

The Lightweight Thrust Chamber program is currently underway at Rocketdyne, part of the Integrated High Payoff Rocket Propulsion Technology program being administered by the Air Force Research Laboratory. Gel-cast, in-situ reinforced silicon nitride, supplied by AlliedSignal Ceramic Components (ASCC) under the trade name AS800, has been selected as the baseline material for development. Materials characterization is complete, and the properties have met or exceeded expectations. Activities to develop a method of joining Si_3N_4 to AS800 are nearing completion. Adequate bond strength has been demonstrated, and issues with the mismatch of the coefficients of thermal expansion and joining the ceramic to metal have been overcome. Throat support hardware to demonstrate the capability of AS800 to scale up is currently in production at ASCC. Fabrication of 60 Klbf injector and combustion chamber manufacturing technology demonstrators (MTDs) utilizing AS800 is underway. Once this task is complete, subscale hardware will be designed, fabricated and hot-fired to demonstrate its ability to meet the IHPRPT goals of a 40% reduction in weight, 50% reduction in cost, 75% reduction in part count, and 3% increase in I_{sp}.

Acknowledgements

The authors would like to acknowledge several individuals who supported preparation of this paper: Doug Twait of AlliedSignal Ceramic Components; and Susanne Ferrell, Mitch Petervary, and Amar Litt of Rocketdyne.

References

1. Department of Defense Publishing Office, FY1997 Defense Technology Area Plan for Space Platforms, 1997.

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